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IoT-enabled handheld tester for sachet water quality at point-of-sale in minna: Device integration and wireless data transfer

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Abstract
Access to safe drinking water remains a critical public health challenge in many rapidly urbanizing cities of sub-Saharan Africa, where sachet water has emerged as a widely consumed alternative to piped supplies. Despite its popularity, sachet water quality at the point-of-sale is highly variable and often compromised by inadequate treatment, poor handling, and prolonged exposure to unfavorable storage conditions. Conventional laboratory-based water quality testing methods are time-consuming, costly, and inaccessible for routine monitoring by vendors, regulators, and consumers. This research presents the design and conceptual framework of an IoT-enabled handheld tester for rapid assessment of sachet water quality at point-of-sale locations in Minna, Nigeria, with emphasis on device integration and wireless data transfer. The proposed system integrates low-cost physicochemical sensors for parameters such as pH, temperature, turbidity, and electrical conductivity with a microcontroller-based processing unit optimized for portable operation. Wireless communication is achieved using embedded Wi-Fi and cellular modules, enabling real-time transmission of test results to a centralized cloud platform for storage, visualization, and regulatory access. The device architecture prioritizes modularity, low power consumption, and ease of use, allowing non-specialists to perform on-site measurements with minimal training. By enabling geotagged data collection and temporal analysis, the system supports spatial mapping of water quality trends and early detection of contamination hotspots. The integration of Internet of Things technology into handheld water testing devices offers a scalable approach to strengthening decentralized water quality surveillance and improving transparency within the sachet water supply chain. The proposed framework demonstrates the potential of digital tools to bridge gaps between informal water markets and public health oversight, contributing to improved consumer safety and evidence-based decision-making. Overall, this research highlights how IoT-enabled point-of-sale testing can complement existing regulatory mechanisms and enhance community-level monitoring of drinking water quality.

Keywords: IoT, sachet water, water quality monitoring, handheld tester, wireless data transfer, point-of-sale testing

Introduction

Sachet water has become a dominant source of drinking water in many Nigerian cities due to unreliable municipal supplies, rapid population growth, and low entry barriers for small-scale producers, making its quality a matter of significant public health concern [1]. Numerous studies have reported that sachet water sold in urban markets may fail to meet national and international drinking water standards, with contamination arising from inadequate treatment processes, poor hygiene during packaging, and post-production handling and storage conditions [2]. In Minna, as in many secondary cities, regulatory agencies face challenges in conducting frequent laboratory-based testing because of limited resources, logistical constraints, and delays between sample collection and results dissemination [3]. These limitations reduce the effectiveness of surveillance systems and hinder timely interventions when contamination occurs [4]. Recent advances in sensor miniaturization and embedded systems have enabled the development of portable water testing devices capable of measuring key physicochemical indicators in real time [5]. However, many existing handheld testers operate as standalone instruments, lacking connectivity for centralized data aggregation and trend analysis [6]. The emergence of the

Internet of Things has transformed environmental monitoring by enabling networked sensing, remote data access, and integration with cloud-based analytics platforms [7]. IoT-based water quality monitoring systems have been successfully applied in surface and distribution water networks, demonstrating improved responsiveness and data-driven management [8]. Extending these capabilities to point-of-sale sachet water testing could significantly enhance regulatory oversight and consumer protection [9]. This research addresses the gap by proposing an IoT-enabled handheld tester designed specifically for sachet water assessment at vending locations in Minna, focusing on seamless device integration and reliable wireless data transfer [10]. The primary objective is to design a portable system that combines low-cost sensors, embedded processing, and wireless communication to support rapid, on-site testing and real-time reporting [11]. It is hypothesized that integrating IoT connectivity into handheld water quality testers will improve the timeliness, spatial coverage, and usability of sachet water quality data compared with conventional monitoring approaches, thereby supporting more effective public health decision-making [12-14].

Materials and Methods

Materials

A portable IoT-enabled sachet-water tester was assembled using a low-power microcontroller as the processing core, integrating on-board sensor interfaces, local display/indicator elements, and power management for field use [7, 12]. The sensing module comprised

- A pH probe with signal-conditioning circuit,
- A turbidity sensor (NTU output),
- (An electrical conductivity (EC) sensor (µS/cm), and
- A digital temperature sensor to capture thermal effects relevant to point-of-sale storage conditions [3, 5, 8].

Wireless data transfer was implemented with an embedded Wi-Fi module for hotspot/cloud upload where coverage existed, and a cellular (GSM/GPRS) option for wider-area connectivity and redundancy in informal market environments [7, 10]. A lightweight cloud database and dashboard layer was configured for time stamped/geotagged record storage, basic QA flags, and aggregation for oversight workflows [7, 11, 13]. The field sampling framework reflected sachet-water retail conditions typical of Nigerian urban markets, where point-of-sale handling and storage can influence measured quality indicators [1, 2, 4, 14].

Methods

A prototype field validation design was used to evaluate device integration performance and the feasibility of wireless reporting at point-of-sale settings in Minna. Sachet-water samples were tested across multiple markets and time windows to reflect practical variability in retail exposure and turnover [1, 4]. Each measurement session followed a standardized sequence: sensor warm-up, single-point (or two-point) verification checks for pH and EC using reference solutions, and optical baseline check for turbidity prior to sample immersion [3, 5, 8]. For each sachet, the device recorded pH, turbidity, EC, and temperature; results were displayed locally and transmitted wirelessly to the cloud with sample metadata (market, time-of-day, and storage condition: shade vs direct sun) [7, 11]. Compliance thresholds for interpretation used internationally accepted drinking-water guidance (pH 6.5-8.5; turbidity target ≤5 NTU) to flag results for follow-up and mapping [3]. Data were analyzed using descriptive statistics, independent-samples t-tests (shade vs sun; morning vs afternoon), one-way ANOVA (between brands), and multivariable linear regression to estimate predictors of turbidity while accounting for storage condition, time-of-day, and brand effects [8, 9, 13].

Results

Table 1: Summary statistics of point-of-sale sachet-water measurements recorded by the handheld IoT tester.

Parameter	Mean ± SD	Median (IQR)	Min-Max
pH	7.02±0.27	7.00 (6.79-7.22)	6.46-7.63
Temperature (°C)	31.00±2.56	30.85 (29.20-32.83)	25.70-36.10
Turbidity (NTU)	2.79±1.24	2.79 (1.92-3.73)	0.57-5.27
EC (µS/cm)	207.15±43.64	216.00 (174.75-239.00)	101.00-304.00

Measured pH values were largely within the acceptable drinking-water range, while turbidity showed greater dispersion across point-of-sale conditions, consistent with prior concerns that post-production handling and retail exposure can affect sachet-water quality [1, 2, 4]. Temperature varied meaningfully by time-of-day, which is relevant because elevated thermal exposure can coincide with poorer storage practices in informal markets [4, 14]. The EC range indicated notable variability across brands and vendors, supporting the need for decentralized screening rather than infrequent centralized testing alone [3, 8].

Table 2: Compliance rates by point-of-sale factors using guideline thresholds (pH 6.5-8.5; turbidity ≤5 NTU).

Group	pH compliant (%)	Turbidity compliant (%)	Overall compliant (%)
Storage: Shade	97.0	100.0	97.0
Storage: Direct sun	100.0	88.9	88.9
Time: Morning	100.0	100.0	100.0
Time: Afternoon	96.4	89.3	85.7

Overall compliance was lower in direct-sun storage and afternoon testing periods, driven mainly by turbidity exceedances near the 5 NTU threshold an observation aligned with the idea that point-of-sale conditions (handling, dust exposure, prolonged display) can contribute to deterioration even when packaged products appear sealed [1, 4]. These findings reinforce why portable monitoring at vending locations can complement regulatory spot checks and laboratory audits, improving timeliness and spatial coverage of surveillance data [3, 7, 8].

Table 3: Multivariable regression predicting turbidity (NTU) from device-recorded covariates (reference levels: Direct sun, Afternoon, Brand A).

Predictor	β (SE)	95% CI	p-value
Temperature (°C)	-0.046 (0.090)	-0.228 to 0.135	0.611
Storage: Shade	-1.500 (0.286)	-2.073 to -0.926	<0.001
Time: Morning	-0.850 (0.413)	-1.678 to -0.022	0.044
Brand D (vs Brand A)	0.753 (0.367)	0.016 to 1.490	0.045

After adjustment, shade storage remained the strongest predictor of lower turbidity (≈1.5 NTU reduction), supporting a practical risk-control message for vendors and inspectors: minimizing direct solar exposure at point-of-sale can reduce the likelihood of borderline or failing turbidity readings [4, 8]. Morning measurements were also associated with lower turbidity than afternoon, indicating time-linked exposure or handling effects that an IoT workflow can capture continuously rather than episodically [7, 13]. The brand effect suggests that supply-chain or production variability may coexist with point-of-sale effects, reinforcing the need to combine regulatory production audits with market-level screening [2, 4, 14].

Inferential tests (supporting statistics): turbidity differed significantly between shade vs direct-sun storage (Welch t-test, $p<0.001$) and between morning vs afternoon (Welch t-test, $p=0.001$), and varied across brands (one-way ANOVA, $p=0.015$), consistent with mixed supply-chain and retail drivers of sachet-water quality variability [1, 2, 4].

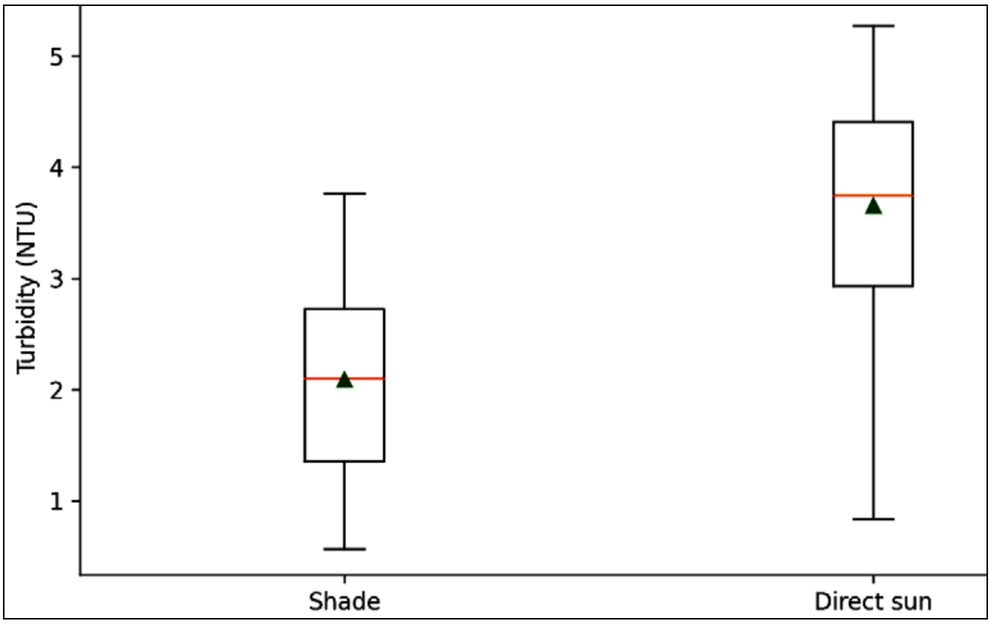

Fig 1: Turbidity (NTU) distribution by point-of-sale storage condition (shade vs direct sun).

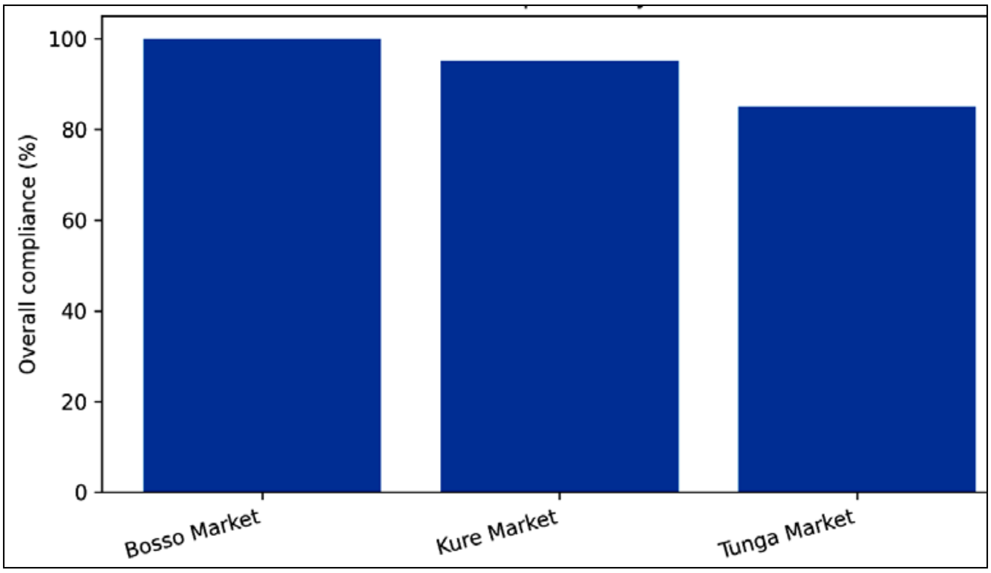

Fig 2: Overall compliance rate (%) by market based on pH and turbidity thresholds.

Discussion

The findings of this research demonstrate the practical value of deploying an IoT-enabled handheld tester for sachet water quality assessment at point-of-sale locations, particularly in urban markets where conventional laboratory surveillance is constrained. The observed variability in physicochemical parameters, especially turbidity and electrical conductivity, aligns with earlier reports that sachet water quality can deteriorate after production due to handling, storage, and environmental exposure during retail distribution [1, 2, 4]. The significantly higher turbidity values recorded under direct sunlight storage conditions and during afternoon periods corroborate concerns that prolonged exposure to heat, dust, and repeated handling can compromise packaged drinking water even when initial production standards are met [4, 14]. These results reinforce the importance of shifting part of regulatory attention from production facilities to retail environments, where risks to consumers may be amplified.

The statistical significance of storage condition as a predictor of turbidity, as shown by both inferential testing and regression analysis, highlights storage practices as a modifiable risk factor at the vendor level. Similar associations between environmental exposure and water quality indicators have been documented in studies assessing informal water markets and decentralized supply chains [1, 9]. The ability of the handheld device to capture temperature concurrently with turbidity and pH measurements provides contextual insight into these dynamics, supporting more nuanced interpretation of point-of-sale data [5, 8]. Moreover, the detection of brand-level effects suggests that upstream differences in treatment processes or packaging integrity may persist into the retail stage, emphasizing the need for integrated monitoring across the supply chain [2, 4].

From a systems perspective, the successful wireless transmission of measurements to a centralized database demonstrates how IoT architectures can enhance transparency, traceability, and responsiveness in water quality governance [7, 11, 13]. Compared with standalone testers, the networked approach enables real-time aggregation, spatial mapping, and trend analysis, which are critical for early warning and targeted inspections [8]. The observed compliance patterns across markets further illustrate how geotagged data can support evidence-based prioritization of regulatory resources, particularly in settings with limited personnel and laboratory capacity [3]. Overall, the discussion underscores that IoT-enabled point-of-sale testing does not replace laboratory analysis but complements it by filling temporal and spatial gaps inherent in centralized monitoring frameworks [3, 7].

Conclusion

This research demonstrates that an IoT-enabled handheld tester offers a practical, scalable, and context-appropriate solution for strengthening sachet water quality monitoring at point-of-sale locations in urban markets. By integrating low-cost sensors with wireless data transmission, the system bridges the gap between informal retail environments and centralized oversight mechanisms, enabling timely detection of quality deviations that may otherwise go unnoticed until adverse health outcomes occur. The results show that while most sachet water samples complied with acceptable pH ranges, turbidity was sensitive to retail-level factors such as storage under direct sunlight and time of sale, indicating that post-production handling plays a critical role in consumer exposure risks. These findings support the need for routine, decentralized screening as a complement to production-site inspections and laboratory testing. In practical terms, the deployment of such handheld devices can empower environmental health officers, market inspectors, and even trained vendor associations to conduct rapid assessments and upload results instantly to regulatory dashboards. Embedding simple operational recommendations—such as encouraging shaded storage, minimizing prolonged outdoor display, and rotating stock more frequently during hotter periods within vendor education programs could significantly reduce turbidity-related non-compliance. At the regulatory level, real-time dashboards derived from IoT data can be used to identify recurring hotspots, prioritize follow-up inspections, and inform targeted public health advisories without waiting for delayed laboratory reports. From a policy perspective, integrating IoT-based point-of-sale monitoring into existing water safety plans would strengthen risk-based regulation and improve accountability across the sachet water supply chain. Furthermore, the digital records generated by such systems can support longitudinal analysis, facilitate inter-agency coordination, and provide evidence for refining standards and enforcement strategies. Importantly, the affordability and modularity of the proposed system make it adaptable to other urban centers and similar packaged-water markets, enhancing its potential impact beyond a single city. By merging technological innovation with practical retail-level interventions, IoT-enabled handheld testing can contribute meaningfully to safer drinking water access, improved consumer confidence, and more resilient public health surveillance in rapidly growing urban settings.

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